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The Eulerian Time Correlation Function in Homogeneous Isotropic Turbulence

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March 2002

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THE EULERIAN TIME CORRELATION FUNCTION IN HOMOGENEOUS ISOTROPIC TURBULENCE

R. RUBINSTEIN* AND GUOWEI HE†

Abstract. Two general models are proposed for the Eulerian time correlation function in homogeneous isotropic turbulence. The first is based on continued fraction approximations to its Laplace transform, and the second is based on random sweeping by a possibly non-Gaussian velocity field. Both models can give reasonable quantitative agreement with DNS data for moderate time separations over which the time correlation functions at different wavenumbers exhibit a common self-similar form.

Key words. time correlation, turbulence, sub-Gaussian

Subject classification. Fluid Mechanics

1. Introduction. The analysis of time correlations in turbulence begins with Kraichnan's explanation [1] of the inconsistency of Eulerian turbulence closures with Kolmogorov scaling. This work revealed that the dynamic decorrelation mechanisms are distinct for Eulerian and Lagrangian time correlations and that energy transfer in turbulence must be analyzed in terms of Lagrangian quantities.

Since Lagrangian time correlations arise both in the problem of energy transfer in turbulence and in the equally fundamental problem of passive scalar diffusion, they would seem to be more important. Nevertheless, Eulerian properties are relevant in a broad class of problems in which turbulence acts as a time-dependent random medium and properties at fixed locations in space are required. Wave scattering by turbulence is one example; provided the turbulence is not simply frozen during the passage of the wave, analysis of this problem will depend on Eulerian time correlations.

Sound radiation by turbulence is another problem in which Eulerian correlations might be relevant. As applied to homogeneous, isotropic turbulence, Lighthill's theory [2] appears to treat fixed regions of space, not moving volumes of fluid, as sound sources. Since the space-time properties of fixed spatial volumes determine the sound source, Eulerian time correlations are relevant. Since the observer defines a coordinate system at rest, Eulerian time correlations are certainly consistent with Lighthill's theory. More generally, Kaneda has suggested that whereas energy transfer in turbulence depends on Lagrangian time correlations, momentum transfer depends on Eulerian time correlations, which also suggests the relevance of Eulerian time correlations to sound radiation.

The Eulerian time correlation function $\psi(r,t)$ is defined in homogeneous, isotropic turbulence by

$$\langle \mathbf{u}(\mathbf{x},t)\cdot\mathbf{u}(\mathbf{x}+\mathbf{r},t+\tau)\rangle = Q(r)\ \psi(r,\tau) \tag{1.1}$$

where

$$Q(r) = \langle \mathbf{u}(\mathbf{x},t)\cdot\mathbf{u}(\mathbf{x}+\mathbf{r},t)\rangle \tag{1.2}$$

is the single-time correlation function.

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†ICASE, Mail Stop 132C, NASA Langley Research Center, Hampton, VA 23681-2199 (email: hgw@icase.edu or guoweihe@yahoo.com). This research was supported by the National Aeronautics and Space Administration under NASA Contract No. NAS1-97046 while the author was in residence at ICASE, NASA Langley Research Center, Hampton, VA 23681.

The basic fact about Eulerian time correlations is the similarity form for inertial range separations [1, 3]

$$\psi(r,\tau) = \psi\left(\frac{V\tau}{r}\right) \tag{1.3}$$

where

$$V^2 = \langle \mathbf{u}(\mathbf{x},t)\cdot\mathbf{u}(\mathbf{x},t)\rangle \tag{1.4}$$

is the *rms* velocity fluctuation.

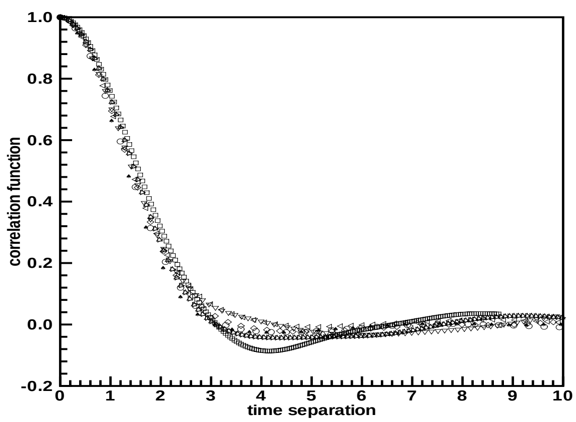

FIG. 1.1. *Time correlation function at various wavenumbers plotted as functions of the similarity variable $\xi = Vk\tau$. The thick curve with the lowest minimum corresponds to a low wavenumber; increasing wavenumber corresponds to increasing $\psi(\xi)$ at $\xi = 4$.*

The validity of the similarity form Eq. (1.3) has been demonstrated repeatedly in the literature [3]. We confirm this similarity form with new observation summarized in Fig. 1.1, which shows the time correlation function in Fourier space, $\psi(k,\tau)$ for various wavenumbers k, plotted as functions of the similarity variable $Vk\tau$. The data is taken from He et al. [4]. The time correlations for all wavenumbers collapse very well for time separations $Vk\tau < 3$. At longer times, the time correlation functions cross zero and oscillate. These features appear to be quite robust, although our data is not sufficiently well resolved to draw definitive conclusions at very long time separations. This behavior is somewhat in contrast to the data of [5], however, we provisionally assume it is correct. Although the correlation functions at different wavenumbers no longer collapse so well when $Vk\tau > 3$, the time correlation functions for wavenumbers in the range $10 < k < 35$, appear to exhibit a common similarity form even in the neighbourhood of the zero-crossing. We tentatively identify these wavenumbers with an inertial range, although the relatively low-resolution (128^3) DNS does not contain an extended region of unambiguous Kolmogorov scaling.

In this paper, we explore some possible analytical forms for the function ψ. Apart from its purely theoretical interest, there are applications in which the precise analytical form of the time correlation is important. In astrophysical applications [6], the total acoustic radiation from stars depends surprisingly sensitively on the assumptions made about the time correlation function. A similar sensitivity to the time correlation function was found by Bertoglio et al. [7].

2. Continued fraction methods. Kaneda et al. [5] curvefit turbulent time correlation functions by rational functions, using the Taylor series approximations and the Padé table. Thus, if for fixed k, we write

$$\psi(k,\tau) = \omega_0(k) + \frac{1}{2!}\omega_2(k)\tau^2 + \frac{1}{4!}\omega_4(k)\tau^4 + \cdots \tag{2.1}$$

then the Taylor coefficients are evaluated as

$$\begin{aligned} \omega_0(k) &= \psi(k,0) = 1 \\ \omega_2(k) &= \frac{d^2\psi}{dt^2}(k,0) = -\frac{\langle \dot{\mathbf{u}}(\mathbf{k},t)\cdot\dot{\mathbf{u}}(-\mathbf{k},t)\rangle}{\langle \mathbf{u}(\mathbf{k},t)\mathbf{u}(\mathbf{k},t)\rangle} \\ \omega_4(k) &= \frac{d^4\psi}{dt^4}(k,0) = +\frac{\langle \ddot{\mathbf{u}}(\mathbf{k},t)\ddot{\mathbf{u}}(-\mathbf{k},t)\rangle}{\langle \mathbf{u}(\mathbf{k},t)\mathbf{u}(\mathbf{k},t)\rangle} \\ &\cdots \end{aligned} \tag{2.2}$$

The time derivatives on the right side can be replaced by single-time moments of the velocity field by applying the Navier-Stokes equations. The time derivative of order n then is given in terms of a single-time moment of order $2n$. This fact connects the time correlation function to intermittency [8].

This method of calculation leads to very good results. Here, a different method is followed, which leads to a rational approximation of the Laplace transform of the correlation function [9]. In molecular hydrodynamics, the correlation function is expressed as a continued fraction through the Zwanzig-Mori projection operator formalism [10]. Recently, this formalism has been generalized to non-equilibrium conditions by [8].

However, we can also give an elementary account as follows. Define the Laplace transform of the time correlation function as usual by

$$\psi(s) = \int_0^\infty d\tau\ e^{-s\tau}\psi(\tau) \tag{2.3}$$

and assume the continued fraction representation

$$\psi(s) = \frac{a_0}{s+}\frac{a_2}{s+}\frac{a_4}{s+}\frac{a_6}{s+}\cdots \tag{2.4}$$

and the Taylor series expansion Eq. (2.1). Substituting Eq. (2.1) in Eq. (2.3),

$$\psi(s) = \frac{1}{s} + \frac{\omega_2}{s^3} + \frac{\omega_4}{s^5} + \cdots \tag{2.5}$$

Equating the expressions for $\psi(s)$ Eqs. (2.4) and (2.5), the Euclidean algorithm gives

$$\begin{aligned} a_2 &= -\omega_2 \\ a_4 &= -\frac{\omega_4}{\omega_2} + \omega_2 \\ a_6 &= -\frac{\omega_4 - \omega_6/\omega_2}{\omega_2 - \omega_4/\omega_2} + \frac{\omega_4}{\omega_2} \end{aligned} \tag{2.6}$$

An obvious approximation method is finite truncation of this continued fraction [10]. We obtain in this way first the the one-parameter or Markovian model

$$\psi(\tau) = e^{-\omega\xi} \tag{2.7}$$

and at the next order, the two-parameter model

$$\psi(\tau) = \left(\cos\tilde{\omega}\xi + \frac{\omega}{2\tilde{\omega}}\sin\tilde{\omega}\xi\right)e^{-\omega\xi/2} \tag{2.8}$$

In Eqs. (2.7) and (2.8), $\xi = Vk\tau$, the similarity variable corresponding to Eq. (1.3)

It should be stressed that an assumption of complete similarity is made in writing Eqs. (2.7) and (2.8), namely that

$$\omega_{2n} \sim (Vk)^{2n} \tag{2.9}$$

This is an assumption of 'normal scaling' for the Taylor coefficients; in view of Eqs. (2.6), it also implies normal scaling of the coefficients in the continued fraction expansion Eq. (2.4). This assumption may be satisfactory for Fourier coefficients [11].

The Markovian model is well-known to be incorrect, because it does not have zero slope at $\tau = 0$. But Fig. 1.1 also suggests that the two-parameter model is qualitatively inadequate, because it predicts equally spaced zeroes of the correlation function. We could proceed to the general three-parameter model, but prefer to consider a special form of this model [10] defined in terms of the *memory function*

$$K(\tau) = \tilde{\omega}^2(1 + \omega\tau)e^{-\omega\tau} \tag{2.10}$$

by the equation

$$\dot{\psi}(\tau) + \int_0^\tau d\tau' K(\tau - \tau')\psi(\tau') = 0 \tag{2.11}$$

Eq. (2.11) is equivalent to a system of ordinary differential equations, expressed in terms of Laplace transforms as

$$\begin{aligned} &s\psi(s) + \tilde{\omega}^2\phi_1(s) = 1 \\ &s\phi_1(s) + \omega\phi_1(s) - \psi(s) - \omega\phi_2(s) = 0 \\ &s\phi_2(s) + \omega\phi_2(s) - \psi(s) = 0 \end{aligned} \tag{2.12}$$

which proves more convenient for numerical evaluation.

Since this is a two-parameter model, it is defined by two properties of the correlation function, which we take to be the *microscale*

$$\tau_\mu^2 = -\frac{1}{\ddot{\psi}(0)} \tag{2.13}$$

and the *integral scale*

$$\tau_M = \int_0^\infty dt\ \psi(t) \tag{2.14}$$

The connection between these quantities and the model parameters is

$$\tilde{\omega}^2 = \frac{1}{\tau_\mu} \tag{2.15}$$

$$2\frac{\tilde{\omega}^2}{\omega} = \frac{1}{\tau_M} \tag{2.16}$$

The generality of this class of functions is evident from the equivalent system of equations Eq. (2.12), which shows that pure exponential decay occurs in the limit $\tilde{\omega} \approx 0$ and that oscillations occur in the limit $\omega \approx 0$. Intermediate behavior can be anticipated between these limits and is confirmed in Fig. 2.1. Trial and

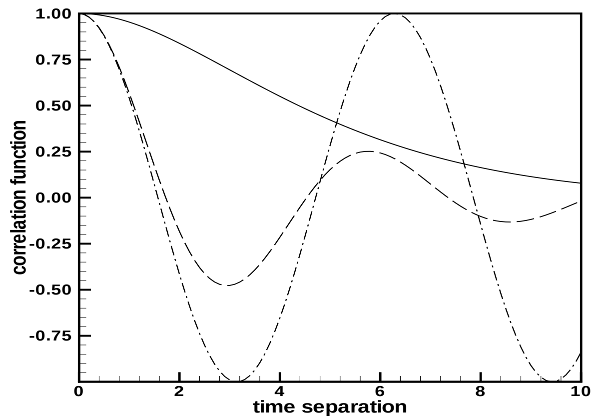

FIG. 2.1. *The two-parameter correlation function of Eqs. (2.10)–(2.11) plotted for various values of the ratio* $r = \tilde{\omega}/\omega$*:* $r = 0$ *(solid),* $r = 1$ *(dashed),* $r = 10$ *(dot-dash). As* r *increases from zero, the function goes from pure decay to pure oscillation.*

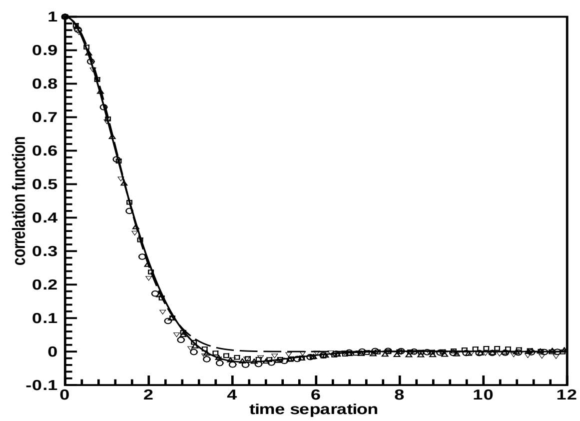

FIG. 2.2. *The correlation function Eqs. (2.10)–(2.11) fit to the data of Fig. 1.1. Symbols are DNS, the solid line is the curvefit, and the dashed line is the best squared exponential curvefit. The fitting was done by trial and error. The region of negative values of the correlation functions is reproduced well by the empirical function.*

error adjustment of the parameters led to an approximation to the measured Eulerian correlation functions which is shown in Fig. 2.2. We emphasize that the relations Eqs. (2.15)–(2.16) were not used to obtain the curvefit.

This result shows that a good fit to the time correlation function can be obtained in principle knowing only the microscale and integral scale. Nevertheless, the fact remains that neither the equations relating the Taylor coefficients and the model parameters Eq. (2.6) nor the system of ordinary differential equations for the correlation function Eq. (2.12) has much apparent physical significance.

3. The random sweeping model. An important theoretical model for the Eulerian time correlation function is provided by the direct interaction approximation [12]. However, the functional form predicted, $\psi(\tau) \sim J_1(\xi)/\xi$ is unrealistically oscillatory.

Another approximation for Eulerian time correlations is based on Kraichnan's model problem for the random sweeping effect [1]. In this problem, a fixed frozen random velocity field $\mathbf{u}(\mathbf{x})$ is advected by a random constant velocity field $\mathbf{v}$. The result is the time dependent field defined by

$$\dot{\mathbf{u}}(\mathbf{k}, t) = -i\mathbf{k} \cdot \mathbf{v}\mathbf{u}(\mathbf{k}, t) \tag{3.1}$$

where

$$\mathbf{u}(\mathbf{k}, 0) = \mathbf{u}(\mathbf{k}) \tag{3.2}$$

so that

$$\mathbf{u}(\mathbf{k}, t) = \exp(i\mathbf{v} \cdot \mathbf{k}t)\mathbf{u}(\mathbf{k}) \tag{3.3}$$

If $\mathbf{v}$ is Gaussian, then

$$\psi(\tau) = \langle \exp(i\mathbf{v} \cdot \mathbf{k}\tau) \rangle = \exp(-V^2\tau^2k^2/2) \tag{3.4}$$

where

$$V^2 = \langle \mathbf{v} \cdot \mathbf{v} \rangle \tag{3.5}$$

The time correlations of the actual turbulent velocity field are approximated by the (ensemble-averaged) time correlations of the velocity field defined in Eq. (3.3) The assumption underlying this model is that the large scales responsible for sweeping in the actual velocity field can be considered independent of the small scales at which the time correlation is evaluated. The first equality in Eq. (3.4) shows that the pdf is related to the frequency spectrum.

It is evident that this model will not provide a very good fit to the data because the measured correlation functions all take negative values. We consider how this model might be generalized to obtain better agreement. If the pdf of v is non-Gaussian, then certainly the second equality in Eq. (3.4) does not apply. There is considerable recent work [13, 14] suggesting that the single-point pdf of velocity fluctuations is not exactly Gaussian, but is instead *sub-Gaussian*: that is, the tails are lighter than Gaussian, in contrast to familiar 'intermittency' behavior.

A simple sub-Gaussian is defined by truncating a Gaussian,

$$p(\mathbf{v}) = \begin{cases} b\exp(-v^2/2V^2) & \text{if } v \leq a \\ 0 & \text{if } v > a \end{cases} \tag{3.6}$$

where the standard deviation $\propto V$ defines the relevant sweeping velocity. Limiting cases of the corresponding correlation function are the squared exponential Eq. (3.4) when $a = \infty$ and

$$\psi(\tau) = \frac{\sin(\xi)}{\xi} \tag{3.7}$$

when $a = 0$. In general, this correlation function satisfies the inhomogeneous differential equation

$$\frac{d\psi}{d\tau} + \frac{1}{2}\tau\psi = -\pi a^2 e^{-a^2} \frac{d}{d\tau} \frac{\sin(a\tau)}{a\tau} \tag{3.8}$$

Fig. 3.1 plots this correlation function for various values of the parameter a.

Although these correlation functions look promising, there is little doubt that the underlying model for the pdf is somewhat artificial. Falkovich and Lebedev [13] have attempted to compute the tail of the single-point velocity pdf. The tail is found to depend on the forcing statistics, and is therefore not universal. Simply to illustrate some possibilities, we follow this article and consider a non-Gaussian pdf with an $\exp(-v^4)$ tail. Suppose, to have consistency with near Gaussian behavior for small deviations from zero, that

$$p(\mathbf{v}) = a\exp[-(v^2+\alpha v^4)/2V^2] \tag{3.9}$$

Then $\psi(t)$ satisfies

$$\alpha\frac{d}{d\tau}\left[\frac{d^2\psi}{d\tau^2}+\frac{2}{\tau}\frac{d\psi}{d\tau}\right]-\frac{1}{2}\frac{d\psi}{d\tau}-\frac{1}{4}\tau\psi=0 \tag{3.10}$$

Note that when $\alpha = 0$, the time correlation function reduces correctly to the squared exponential form corresponding to a Gaussian-distributed sweeping velocity. Two typical forms of this function are shown in Fig. (3.2).

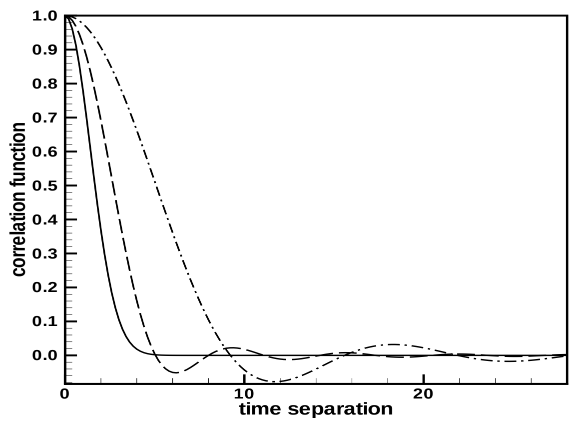

FIG. 3.1. *The one-parameter correlation function defined by Eq. (3.8) plotted for various values of the parameter a: $a = 100$ (solid), $a = 10$ (dashed), $a = 1$ (dot-dash). The limiting cases are $\psi(\xi) = \exp(-\xi^2)$ when $a = \infty$ and $\psi(\xi) = \sin(\xi)/\xi$ when $a = 0$.*

We note the existence of asymptotic solutions to Eq. (3.10)

$$\psi(\tau) \sim \cos(\sqrt{3}\xi^{4/3}/2+\phi)\exp(-\xi^{4/3}/2) \tag{3.11}$$

This solution indicates that the correlation function falls off considerably more slowly than $\exp(-\xi^2)$ and that the correlation function crosses zero with increasing frequency as $\tau \to \infty$. In this respect, the simpler model Eq. (3.6) seems more realistic, but the fact is that the available data do not rule Eq. (3.11) out.

In Fig. (3.3), this function is compared to the empirical distribution corresponding to a variety of wavenumbers k. Again, the curvefitting was done by trial and error, with no attempt to determine the best fit from numerical properties of the measured correlation function. A best fit squared exponential is included for comparison. This figure shows that the low k correlation function is fit remarkably well by this type of function.

Despite the good fit for the low wavenumber case, these sub-Gaussian models are generally too 'elastic' in comparison to the data: the negative amplitude after the first zero crossing tends to be larger than the data, and it tends to recover too quickly. This raises the question of the accuracy of the data in this range. More accurate measurements should be made in order to make more definitive comparisons.

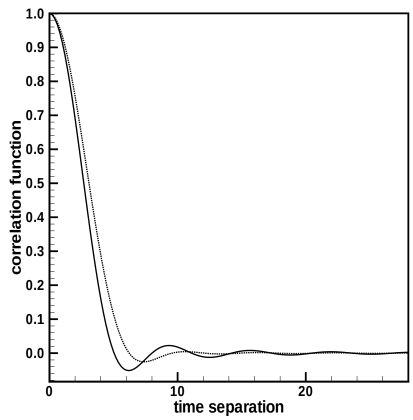

FIG. 3.2. *The one-parameter correlation function defined by Eq. (3.10) plotted for two values of the parameter α: $\alpha = 100$ (solid), $\alpha = 10$ (dotted).*

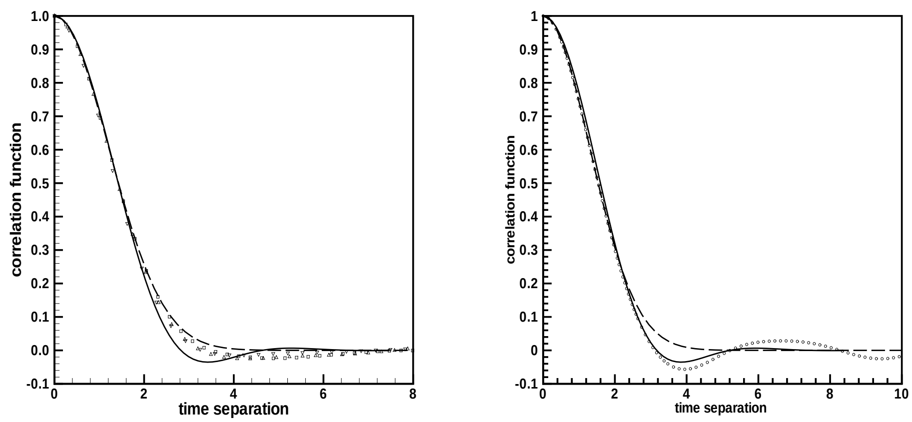

FIG. 3.3. *The correlation function Eq. (3.10) fit to the data of Fig. 1.1. Symbols are DNS, the solid line is the curvefit, and the dashed line is the best Gaussian (squared exponential) curvefit. The graph on the left corresponds to relatively high wavenumbers, the graph on the right to a low wavenumber. The Gaussian provides a good fit to the high wavenumber data, but at low wavenumber, the sub-Gaussian provides much better agreement.*

4. Conclusions. The collapse of the Eulerian time correlation function to a self-similar form based on the sweeping velocity is confirmed by DNS data. For moderate time-separations, the collapse is excellent for all wavenumbers, and continues for larger time separations for inertial range modes. Models for the time correlation function based on continued fraction approximation and on a random sweeping model can both give satisfactory agreement with the data. More accurate measurements of the time correlations at large time separation will be required to refine these models.

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